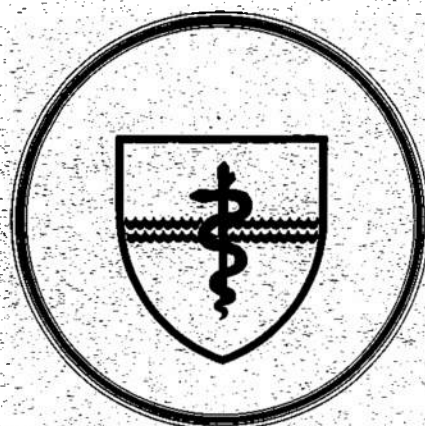


**NAVAL SUBMARINE MEDICAL  
RESEARCH LABORATORY  
SUBMARINE BASE, GROTON, CONN.**



REPORT NUMBER 905

THE LIMITING EFFECTS OF ASTIGMATISM  
ON VISUAL PERFORMANCE THROUGH PERISCOPES

by

S. M. Luria  
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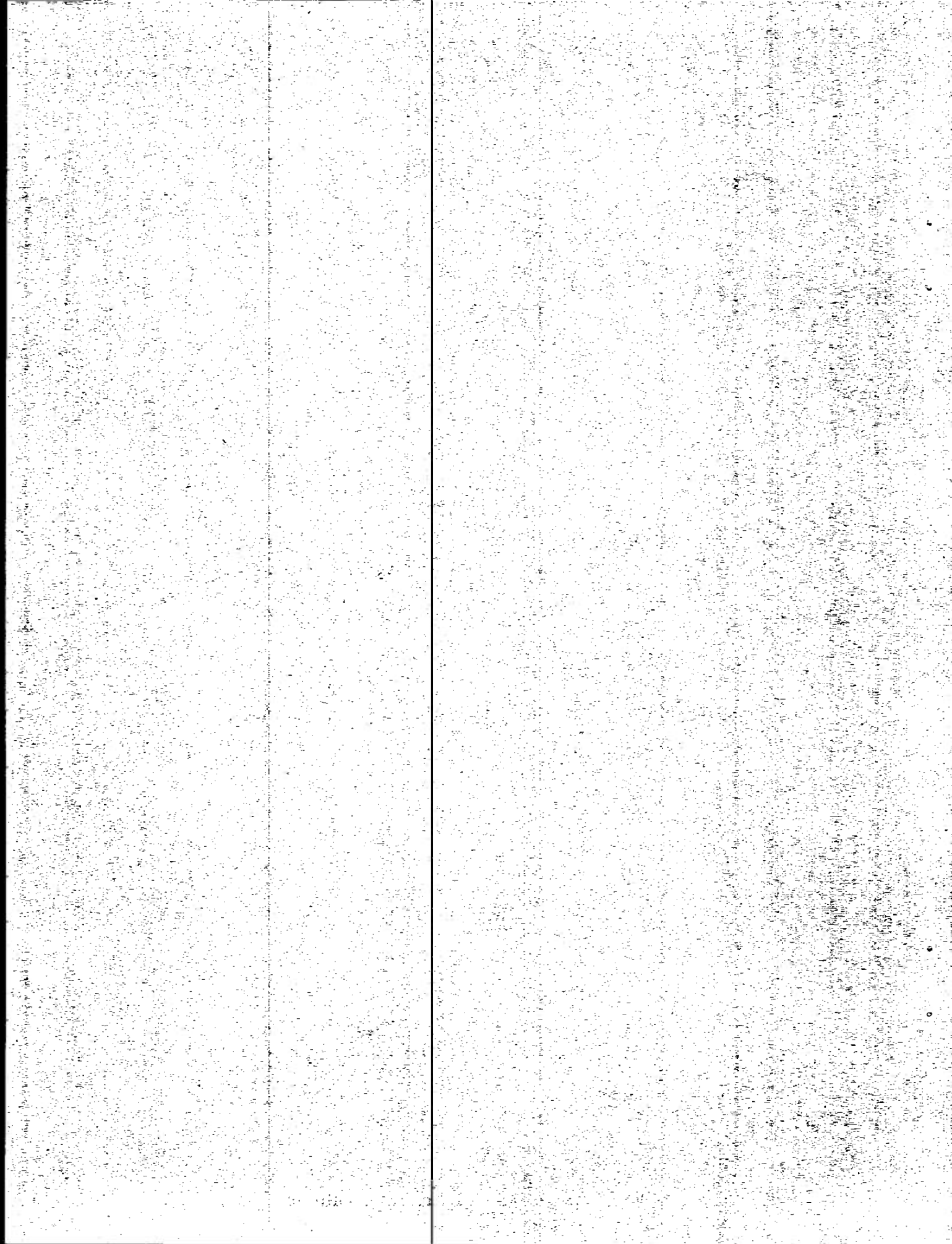
Naval Medical Research and Development Command  
Research Work Unit MF58.524.006-2195

Released by:

R. A. Margulies, CDR, MC, USN  
Commanding Officer  
Naval Submarine Medical Research Laboratory

28 September 1979

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#### PROBLEM

To determine if the new periscopes make it possible to relax the Navy standards for astigmatic periscope operators.

#### FINDINGS

In daytime viewing, 4 diopter astigmats using the new 12X periscope and 6 D astigmats using the new 24X periscope perform as well as 2 D astigmats (the most currently permitted by Navy standards) through the old periscope.

#### APPLICATION

These results are pertinent to a review of the Navy's astigmatism standards for periscope operators.

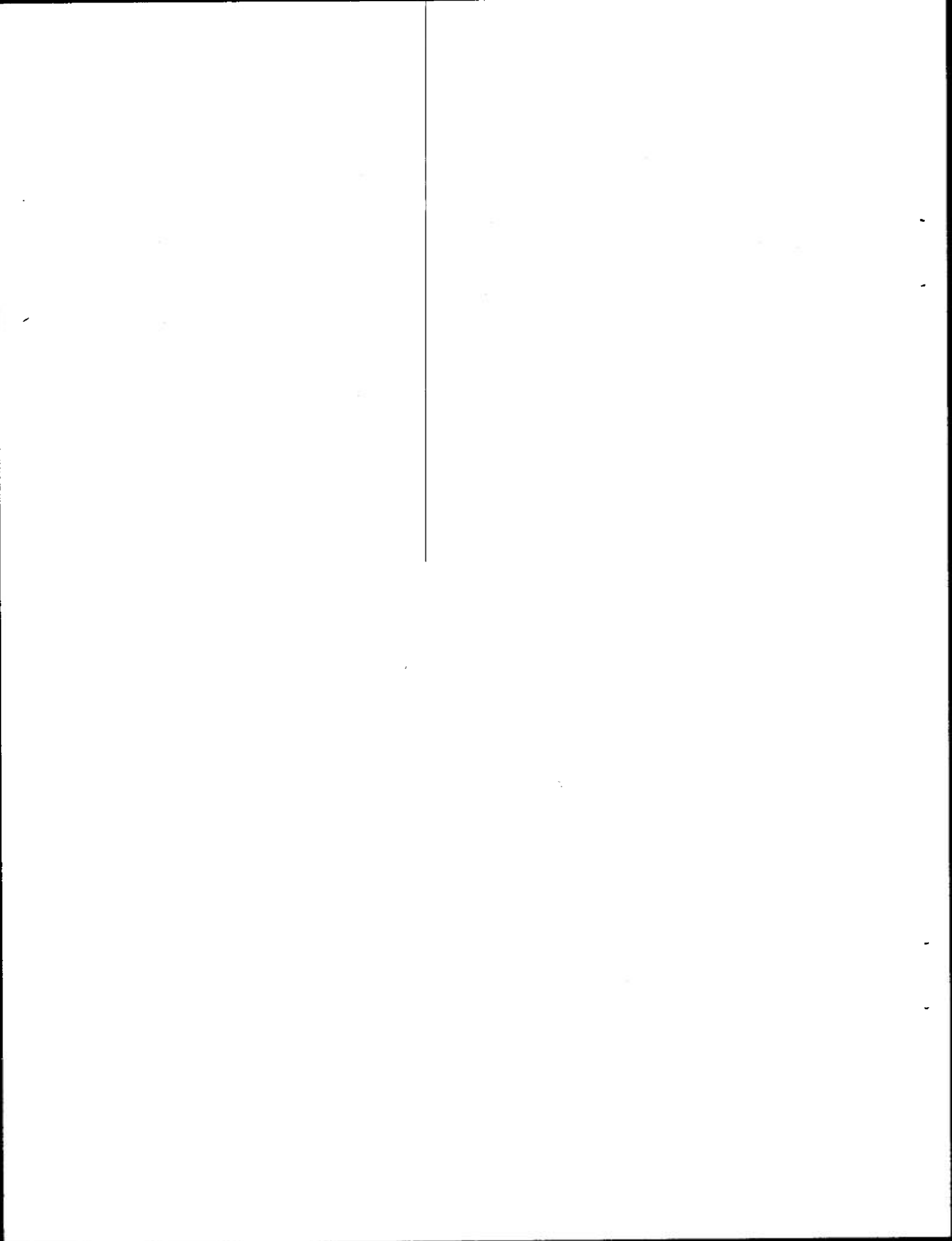
#### ADMINISTRATIVE INFORMATION

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## ABSTRACT

The performance of observers with various degrees of astigmatic error (ranging from 0 to +6D) was compared through the old and new periscopes. In daytime viewing, observers with 4D of astigmatism could see as well through the new 12 power periscope as observers with 2D (the present maximum allowed under Navy standards) could see through the old periscope. With the new 24 power periscope, observers with 6D of astigmatism did even better than 2D astigmats through the old periscope. Additional experiments showed that equivalent results are obtained with either gratings or ship silhouettes, and whether natural or unduced astigmats are the observers.



## OVERVIEW

The Submarine Fleet has clearly defined visual standards, and the Navy loses otherwise qualified individuals because of visual defects. Moreover, it is becoming more difficult to find men who meet all standards. The most widely prevalent defect is astigmatism. Unfortunately, it is difficult to correct optical instruments for astigmatic errors, and it is equally difficult to look through a periscope while wearing glasses. For this reason, astigmatism standards are particularly stringent for men who will be periscope operators, and an appreciable percentage of men is liable to be disqualified from submarine service on this account.

However, a new generation of periscopes has been introduced whose optics far surpass those of the older periscopes. It is possible that visual standards can now be relaxed, because the improved optics make it possible for an astigmatic observer to see more through the new periscope than a normal operator could see through the old ones. This series of experiments examined whether or not current standards for astigmatism could be reduced.

The effects of astigmatism could be tested by measuring the ability of observers to see a wide variety of natural objects, such as ships, shore configurations, islands, lights, and the like. It would be better, however, if a single, universal type of target could be used. Fortunately, one is available: Grating targets of varying spatial frequency have been used for some time to measure the response of complex optical systems, and they are now increasingly being used to evaluate the human visual system. The first experiment, therefore, investigated whether or not the effects of astigmatism could be measured using simple grating targets of varying width. Two diopters of astigmatism, the current maximum allowed in submarines, was induced in subjects and their ability to see gratings of different spatial frequencies was compared to their performance when fully corrected. All four subjects showed the best sensitivity at 2 cycles per degree (cpd) when fully corrected, with sensitivity falling off rapidly on either side. With 2 diopters of astigmatism induced perpendicular to the target stripes, sensitivity to the high spatial frequencies (small stripes) was worse by an order of magnitude, but sensitivity to the low spatial frequencies (large stripes) was unaffected. These results show, first, that the effects of astigmatism can be assessed using grating targets of different spatial frequencies. Moreover, they show that astigmatism will not impair the ability of an individual to see large targets, but it will profoundly reduce his ability to see fine detail.

The second experiment investigated whether natural astigmats give the same results as those obtained with induced astigmats, and whether or not these results do, in fact, apply to more practical targets - ship silhouettes. The maximum distance at which subjects could correctly identify a series of silhouettes of American and Soviet ships was measured when they were fully corrected and under various degrees of induced astigmatism ranging from +0.75 to +4.0 diopters. Despite the fact that identification of ships is presumably a complex cognitive as well as a perceptual task, performance declined as the amount of astigmatism increased; even the smallest amount of astigmatism (.75 D) produced a measurable decline in performance. With 2 D of astigmatism, the distance at which errorless performance occurred was half that when the observers were fully corrected. When the sizes of the ships at threshold are converted to cycles per degree, the results conform with those found with the grating targets. There appears to be no reason, therefore, why simpler targets cannot be used in place of the ships. Moreover, the results for a group of natural astigmats was quite similar to those for the induced astigmats, indicating that it is not necessary to use natural astigmats as subjects.

The final and major experiment in the series measured the ability of subjects with various degrees of astigmatic error to see large and small grating targets at 2800 yards through both the old and new periscopes. The aim was to determine the maximum degree of astigmatism which permitted the same performance through the new periscope that was possible through the old periscope by observers with the maximum degree of astigmatism presently allowed by Navy standards. The results showed that the higher magnifications provided by the new periscopes did much to outweigh the detrimental effects of the astigmatic errors. Specifically, at 12 power of magnification through the new periscope, the subjects with 4 D of astigmatism could see gratings as small as could be seen by observers with 2 D of astigmatism through the old periscope with its magnification of only 6X. When looking through the new periscope at 24 X, observers with 6 D of astigmatism could see appreciably more than could be seen through the old periscope with only 2 D of astigmatism. When presented with targets of low spatial frequency, the detrimental effects of astigmatism were, as predicted, minimal. Thus, the increase in magnification afforded by the new periscope has a beneficial effect for two reasons: First, target size is increased, allowing smaller sized targets to be seen. Second, the increase in target size may bring it into the range of low spatial frequencies that are not affected by astigmatism.

One other finding of interest is that performance through the new periscope is not as good as through the old periscope given the same magnification. The reason is that part of the available light is diverted to the camera and TV monitor. It is not clear if this will affect the performance of the periscope operators at night. If it does not, there seems to be no reason why astigmatism standards cannot be relaxed to permit periscope operators with at least 4 D of astigmatism.



## INTRODUCTION

The Submarine Fleet has clearly defined visual standards, but these standards change from time to time to take account of changes in both the submarines and in the pool of available manpower. One of the problems now confronting the Navy in its recruitment efforts is the loss of otherwise qualified individuals because of visual defects. Such defects have apparently been increasing appreciably during the last generation<sup>8</sup>, and it is becoming more difficult to find men who meet the visual standards.

There are three kinds of visual defects which are covered by Navy standards: color defects, spherical refractive errors, and cylindrical refractive errors. The problem of color-defectives, who make up about 10% of the population, has long been given considerable attention. The other two defects, which manifest themselves as reductions of visual acuity, also interfere with the performance of duties in a submarine, but they are in principle easily correctible with the proper lenses. Indeed, the use of eyeglasses by many men is essential for the performance of their duties on the submarine, since many tasks require 20/20 vision.<sup>7</sup> Spherical errors can also be corrected with lenticular additions to optical instruments - and a fairly sizeable amount of correction for spherical errors is built into periscopes - but it is very difficult to correct for cylindrical refractive errors. These errors, which produce the visual defect called astigmatism, must be corrected with carefully fitted eyeglasses. Unfortunately, it is difficult to look through the periscope while wearing glasses. It is for this reason that visual standards, particularly for cylindrical errors, are more stringent for men whose duties involve the use of the periscope.

Yet, according to optometric authorities, astigmatism is the visual defect that is "undoubtedly the most widely prevalent anomaly presented for correction.<sup>3</sup>(p.127) It is found in more than 80% of all patients examined.<sup>1</sup> Twenty years ago, Hofstetter<sup>5</sup> reported that 14% of individuals in the 20-29 age group had astigmatism. In our survey of 1000 submariners - men constituting a highly selected sample who had already been screened to eliminate large amounts of astigmatism - we found that 56% had the defect. It appears, therefore, that an appreciable percentage of men is liable to be disqualified from submarine service on this account.

There are, however, reasons for questioning whether the visual standards need to be as strict as they are. The Submarine Fleet has recently introduced a new generation of periscopes whose optics far surpass those of older periscopes. The goal of this series of experiments, therefore, was to determine whether or not the current

standards for astigmatism could be reduced and, if so, to what extent. Two laboratory studies and one field experiment are included in this report.

## EXPERIMENT I

### VISUAL CONTRAST SENSITIVITY WITH VARIOUS DEGREES OF ASTIGMATISM

J. A. S. Kinney

One means of answering the question of whether or not individuals with different degrees of astigmatism can see as well through the new types of periscopes as men with no astigmatism would be to compare their performance using a wide variety of natural targets. These could include ships of various shapes and sizes, islands, shore configurations, lights, etc. A more parsimonious technique, however, would be to use a single, universal type of target. Theoretically, such a technique is fortunately available: the determination of contrast sensitivity for different spatial frequencies.

This method arises from the application of Fourier analysis to optical systems; any two-dimensional pattern or form can be broken down into its constituent sine waves which vary in spatial frequency, amplitude, and phase. The response of any system can then be predicted from knowledge of the Fourier components and of how the system responds to each component in isolation. This technique has been widely used in electro-optics for many years, and it is now being applied to the human visual system. Numerous successful tests of the theory in the past 10 years have led many investigators to hypothesize that the human visual system performs Fourier analyses on stimuli and that these data are the basis for the perception of form and pattern.

The usefulness of this technique for the solution of our problem was tested in this experiment by determining the effect of astigmatism on contrast sensitivity. Two diopters of astigmatism, the current maximum allowed in submariners, was induced at various meridional orientations and its effects measured on different spatial frequencies of vertical sinusoidal gratings. In order to test the assumption of the universality of the measure, contrast sensitivity for square waves was also measured in the same individuals, to see if these data could be predicted from the thresholds for the sine waves.

#### Apparatus and Method

Vertical sinusoidal and square-wave gratings were generated on a Hewlett-Packard cathode ray tube with a P31 phosphor by conventional techniques.<sup>11</sup> The mean luminance of the scope was 4.5 cd/m<sup>2</sup> and its angular subtense was 10.5 x 13.5 degrees at the viewing distance of

114 cm. The surround was dimly illuminated to  $.1 \text{ cd/m}^2$ . Five spatial frequencies, .2, .5, 2, 5, and 10 cycles per degree (cpd), were chosen to adequately sample human sensitivity to different spatial frequencies.

Four subjects were employed, either fully corrected for the observing distance of 114 cm or with induced astigmatism of 2 diopters. The astigmatism was always positive, so that the subjects would be unable to accommodate for it, and was oriented at 090, 135, or 180 degrees.

Five levels of modulation were selected for each spatial frequency to range from zero to an easily perceptible grating. Each level was presented twice in a given session. All five levels at all five spatial frequencies were combined and randomized for a total of 50 judgments per session. The subject's task on each presentation was simply to state whether or not stripes were perceived. Two sessions were run for each condition of astigmatism so that final limens for each spatial frequency were based upon 20 judgments.

### Results

The mean data for the four subjects viewing sinusoidal gratings is given in Figure 1. The shapes of the curves are the same for every subject. When fully corrected, contrast sensitivity for every subject is best at 2 cpd and falls rapidly in either direction; the curve is in agreement with many in the literature for these experimental conditions. With two diopters of astigmatism induced at 180 degrees (that is, parallel to the orientation of the stripes), there is no deterioration in contrast sensitivity at any spatial frequency. This too is in agreement with the literature and stems from the fact that a point source delivered to an astigmatic eye does not form a point; rather the astigmatic eye images it in two focal planes parallel to the axes of maximum and minimum power.<sup>3,9</sup>

With the astigmatism induced at 90 degrees (perpendicular to the stripes), sensitivity to low spatial frequencies (that is, large stripes) is unaffected while sensitivity to high spatial frequencies (small stripes) is worse by almost a log unit. With an intermediate orientation of the stripes, the loss of sensitivity is intermediate.

The fact that astigmatism affects the high spatial frequencies stems from the defocusing of the image and occurs in all optical systems. The amount of deterioration depends, of course, on the amount of blurring. While there are no data in the literature on the effects of astigmatic blurring - only spherical blurring - the present data on the effect of astigmatism fit well with the results obtained for blurring by spherical lenses. For example, Campbell, Kulikowski and Levinson<sup>4</sup> report .35 log units of degradation at all frequencies above 5 cpd for .5 D of spherical blur, Regan's<sup>10</sup> measures show .6 log units of degradation

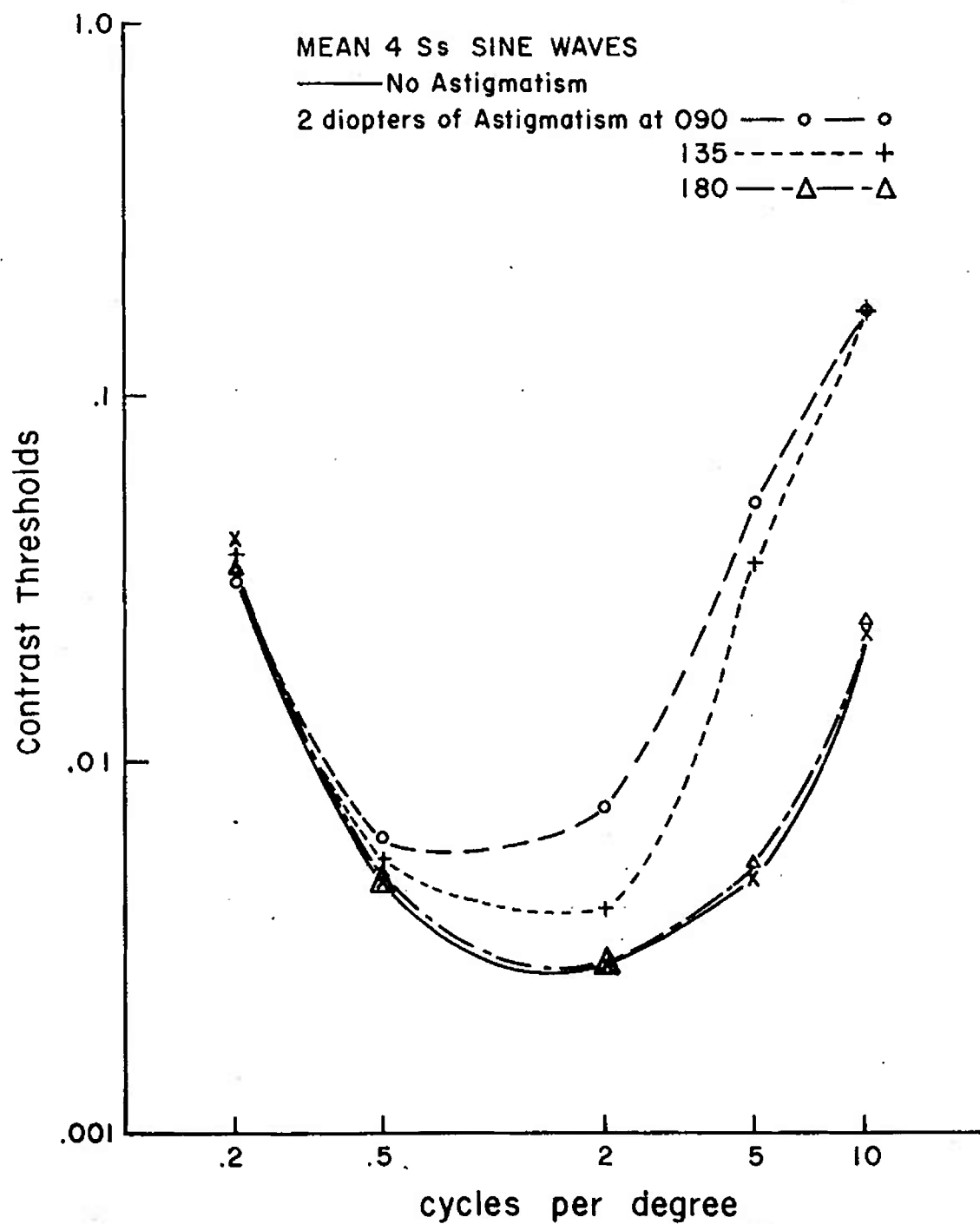


Fig. 1. Mean contrast sensitivity for vertical sinusoidal gratings of 4 subjects with no astigmatism and with 2 diopters of astigmatism of 090°, 135° and 180°.

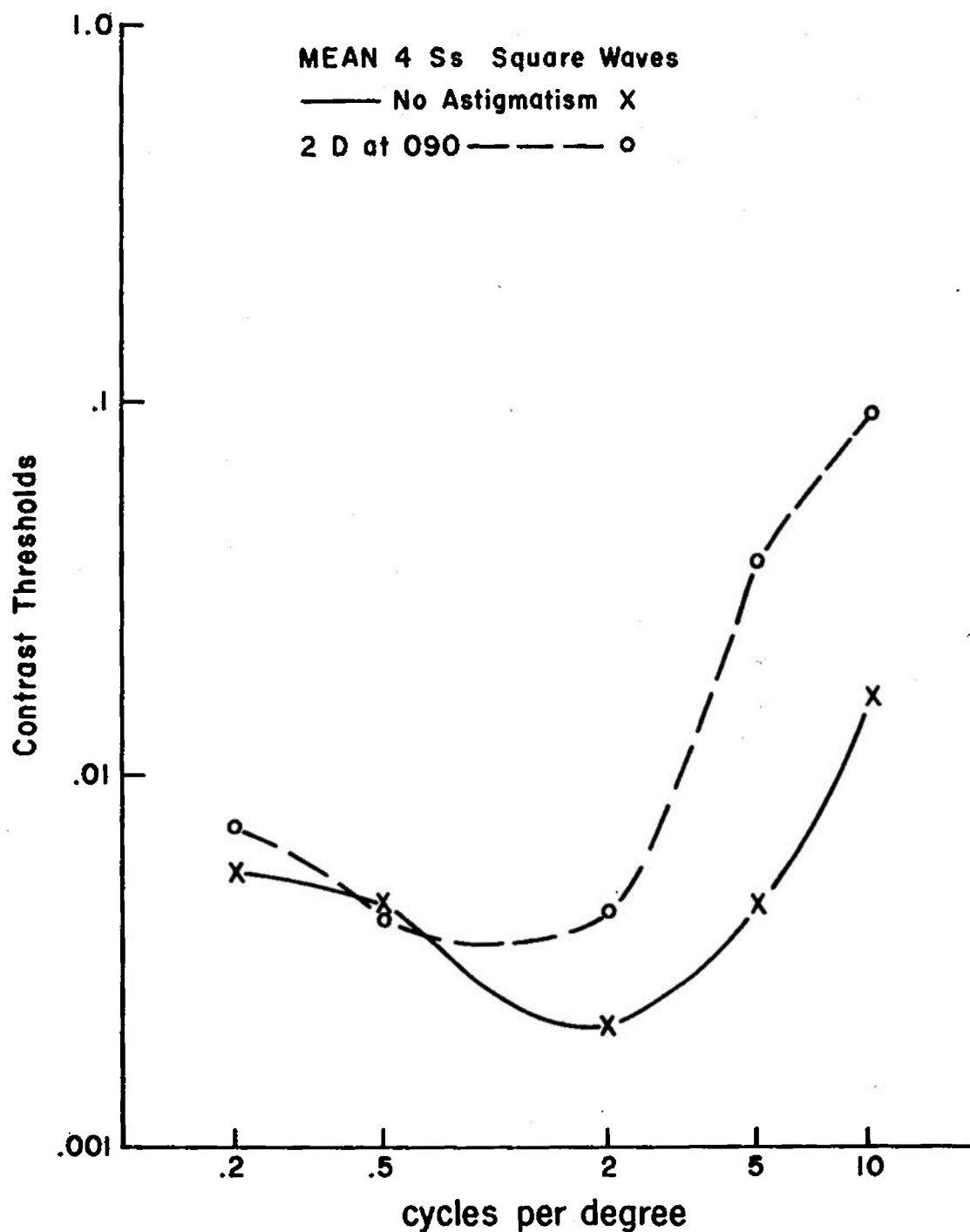


Fig. 2. Mean contrast sensitivity for vertical square waves for 4 subjects with no astigmatism (X) and with 2 diopters of astigmatism at 090° (O). Compare these curves with the analogous curves in Fig. 1 for the same subjects.

for 1 D of spherical defocusing, and these data reveal 1.0 log unit for the 2 D of astigmatism in the worst meridian.

A common technique for testing the Fourier theory is a comparison of sensitivity to sine waves and square waves.\* The result using square waves are given in Figure 2 for the same four subjects whose results using sine waves are shown in Figure 1. With the subjects appropriately corrected, the difference between sensitivity to square waves and sine waves is as predicted from the theory. Thus at .5 cpd and higher spatial frequencies, there are no differences between the two sets of curves other than that of amplitude, and the factor of 1.27 adequately describes the data. This implies that there are no harmonics involved in the square wave sensitivity, nor should there be theoretically.

At .2 cycles per degree, however, sensitivity to square waves (Fig. 2) is much greater than that of sine waves (Fig. 1) and could be mediated for these data by both the first harmonic at .6 cpd (3f) and the second at 1.0 cpd (5f). With astigmatism reducing the sensitivity to sinusoids around 1.0 cpd and beyond, the theory predicts a loss of sensitivity to square waves at .2 cpd (due to loss of the 2nd harmonic) but not at .5 cpd. This in fact occurred: the ratio of square wave to sine wave sensitivity was reduced from 7.5 to 4.7 with 2 D of astigmatism, at .2 cpd, while there was no reduction at all at .5 cpd.

### Conclusions

Sensitivity to low spatial frequencies (large targets) is unaffected by 2 diopters of astigmatism. However, gross changes in sensitivity are found at higher spatial frequencies (small targets) when the astigmatism is oriented perpendicular to the direction of the target stripes. As predicted by Fourier theory, the perception of complex targets can be predicted from the individual's sensitivity

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\* Fourier analysis of a square wave at a given spatial frequency yields the 1.27 times the amplitude (A) of the fundamental, f (the sine wave at the same frequency), plus odd number harmonics at regularly decreasing amplitudes:  $1/3 A(3f) + 1/5 A(5f) + 1/7 A(7f)$  etc. Thus, for a given harmonic to be involved in the sensitivity to a specific square wave, the sensitivity to it must be proportionally increased. At 3f, for example, sinusoidal sensitivity must be 3 times as great as at f to produce an equal contribution. This condition is met only for very low spatial frequencies, thus predicting sizeable differences between sensitivity to square waves and sine waves only for low spatial frequencies.

to sine waves.

These results have two important implications. First, astigmatism will not hinder an individual when he is viewing very large, low contrast targets, but it will profoundly reduce his ability to see fine detail. Second, contrast sensitivity for targets of different spatial frequencies can be employed to assess the astigmatism on other targets.

The implications for the practical situation are that men with currently acceptable amounts of astigmatism will see as well as emmetropes as long as the ships to be viewed are close. However, their abilities to detect small, distant objects and to differentiate ships are inferior to those of individuals without astigmatism.

## EXPERIMENT II

### EFFECTS OF ASTIGMATISM ON RECOGNITION OF SHIPS

S. M. Luria

The first experiment showed the effects of astigmatism on the ability to perceive grating targets. Although these targets are an excellent measure of the functioning of the visual system, and the results indicated that it was possible to predict an individual's performance on complex targets from his performance on sinusoidal gratings, it is worthwhile to test whether or not the results in Experiment I can be generalized to the class of targets of most concern to submariners - ships. Will the same relationship hold when the periscope operator must deal with targets much more complex than gratings, targets which presumably involve not only visual acuity but cognitive processes as well? To answer this question, a second experiment was carried out in which observers attempted to identify ships under various degrees of astigmatism.

In addition, a second question was posed. Are the results of such experiments carried out with artificially induced astigmats equivalent to the results obtained with natural astigmats?

#### Method

Targets - The targets were a series of eight silhouettes of American and Soviet warships prepared from *Jane's All the World's Fighting Ships*.<sup>6</sup> The drawings were black on white cardboard, drawn to scale (1:1800) and they ranged in length from 3 to 5 inches.

Subjects - Ten individuals with no astigmatism, including two who participated in Experiment I, and 15 natural astigmats served as observers. All but two of the emmetropes and one of the astigmats were staff members of the Laboratory.

Procedure - The object of the experiment was to measure the farthest distance at which the observer could identify correctly, under various degrees of astigmatic error, all eight silhouettes. The observers were given the original set of drawings before the experiment so that they could familiarize themselves with them, and they were permitted to refer to the drawings, without any refractive error, in identifying the silhouettes during the experiment. Since the observers could consult the drawings of the ships at any time, their task was one of discrimination of details, rather than detection of the ship. In this set of silhouettes, most of the details to be discriminated lay in the vertical dimension.

The measurement of each distance threshold was begun with the observer close enough to the targets to identify all the silhouettes as they were repeatedly shown in haphazard order. The distance of the observer to the targets was then increased in 5-ft increments until an error was made.

Five magnitudes of cylindrical refractive error were induced: 0, +0.75, +1.50, +3.0 and +4.0 diopters, presented in random order. The axis of astigmatism was vertical; this produces minimal effect on the perception of horizontal details. These five conditions were presented in a different random order to each observer.

The targets were displayed at the end of a long corridor. The luminance, reflected from a white card set up in place of the targets, was 12 ft-L, as measured by a Spectra Spot photometer/radiometer.

### Results

The mean distance from the targets at which the non-astigmatic observers could identify all the target silhouettes under the various levels of induced cylindrical error is shown in Figure 3. With no induced astigmatism, the emmetropes could maintain errorless performance up to a distance of more than 25 ft, at which point the smallest ship subtended about .6 degrees of visual angle. As the magnitude of induced astigmatism increased, the viewing distance had to be decreased until with a +4.0 diopters of refractive error, the observers had to be within 5 ft of the targets in order to identify them all, at which point the smallest ship subtended over 3 deg visual angle. It may be noted that a destroyer hull would subtend .5 deg visual angle (1 cpd) at a distance of 17,000 yards and a visual angle of 3-1/4 degree (.15 cpd) at a distance of 2500 yards.



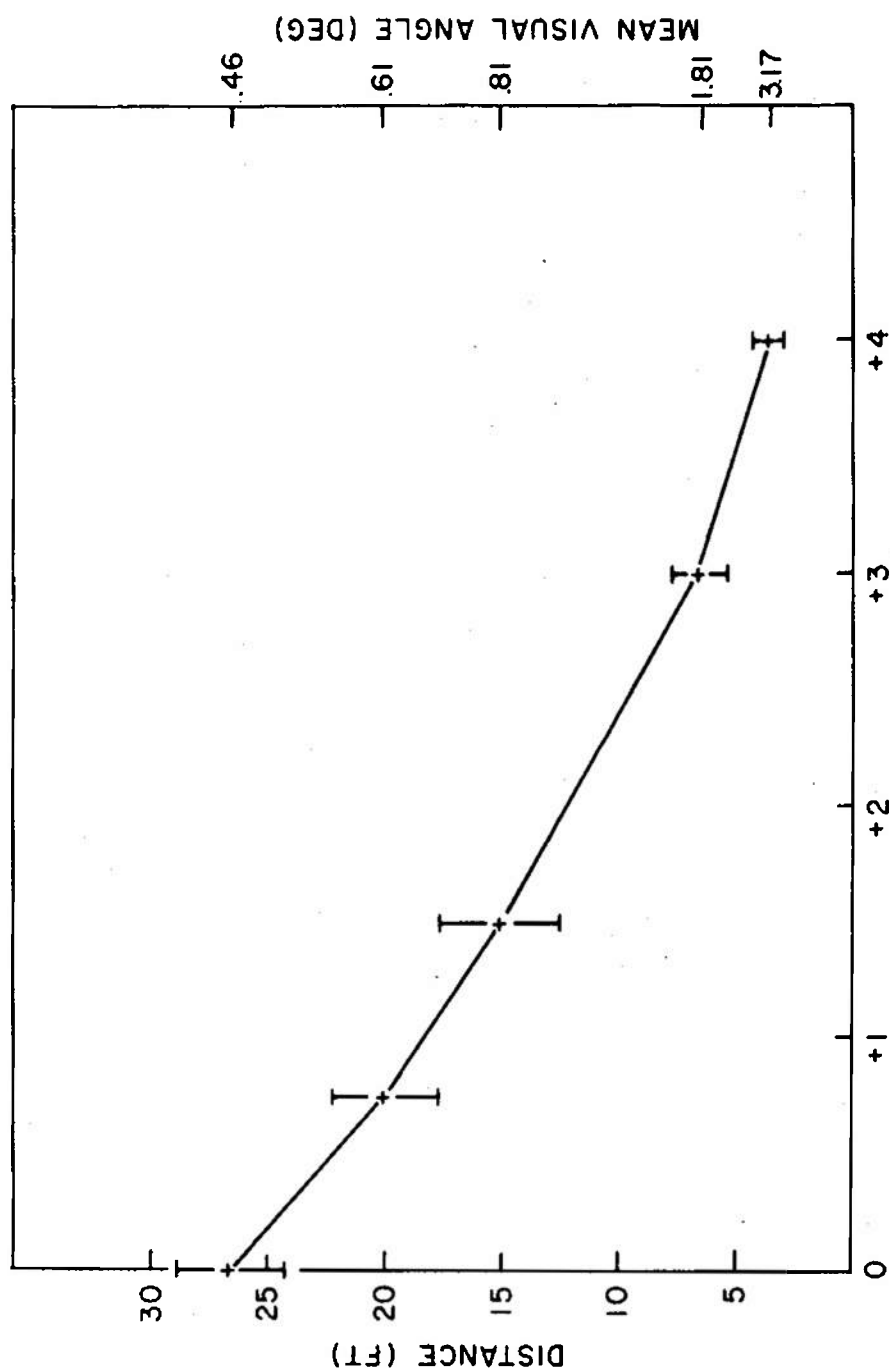


Fig. 3. Mean farthest distance at which all ship silhouettes could be correctly identified through cylinders of various powers. The direction of the distortion was vertical. The vertical lines indicate the standard error of the means.

### Comparison of natural and induced astigmatism

To determine if natural astigmats would have produced similar results, 15 astigmats were then tested both fully corrected and uncorrected for their astigmatism (that is, corrected only for spherical errors). In order to compare them with the results from the emmetropes, Figure 3 has been replotted to show the percent of degradation. For example, since their mean threshold distance of 26.5 ft with no cylindrical error was reduced to 20 ft when there was .75 diopter of error, the percent of degradation was calculated at  $6.5/26.5$ , or 24.5%. The percent of degradation was similarly calculated for each astigmatic observer. These results are presented in Figure 4. The solid line shows the threshold for the emmetropes. Each astigmat is plotted individually. The points for the natural astigmats are reasonably close to the regression line for the emmetropes.

### Effect of orientation of astigmatism

Experiment I showed that the thresholds for the grating targets were unaffected when the axis of astigmatism was parallel to the stripes. It is of interest to measure the effect of the orientation of the astigmatism on ship recognition. To test this, 10 emmetropes were tested with the axis of a +2.0 D cylinder oriented either vertically, horizontally, or obliquely. The three conditions were given in a different random order to each observer. The results are shown in Figure 5. In agreement with Expt. I, every observer identified the ships at the greatest distance when the axis of the cylinder was vertical; however, each observer required the shortest distance when the axis was oblique. Apparently, there are pattern cues on which to base identification of ships in the horizontal as well as the vertical direction. Disturbing one of these sets still leaves the other. For the oblique axis, which disturbs both, leaves the observer relatively little on which to base a decision. This effect cannot be shown with one dimensional gratings.

### Comparison of grating and ship thresholds

The conformity of the two sets of results is evident when a detailed comparison is made. The identification of ships, based upon the discrimination of their details, is obviously a high spatial frequency task. Thus, we would expect a decrement in performance as soon as any astigmatism is introduced. Indeed, we found that even .75 D produced a small decrement in the ability to identify the ships.

The mean threshold distance for errorless identification with no astigmatism was 26.5 ft; at this distance, the smallest ship subtended 38 min arc, or .79 cpd, which is already within the region affected by astigmatism, as shown in Fig. 1. With 4.0 D of astigmatism,

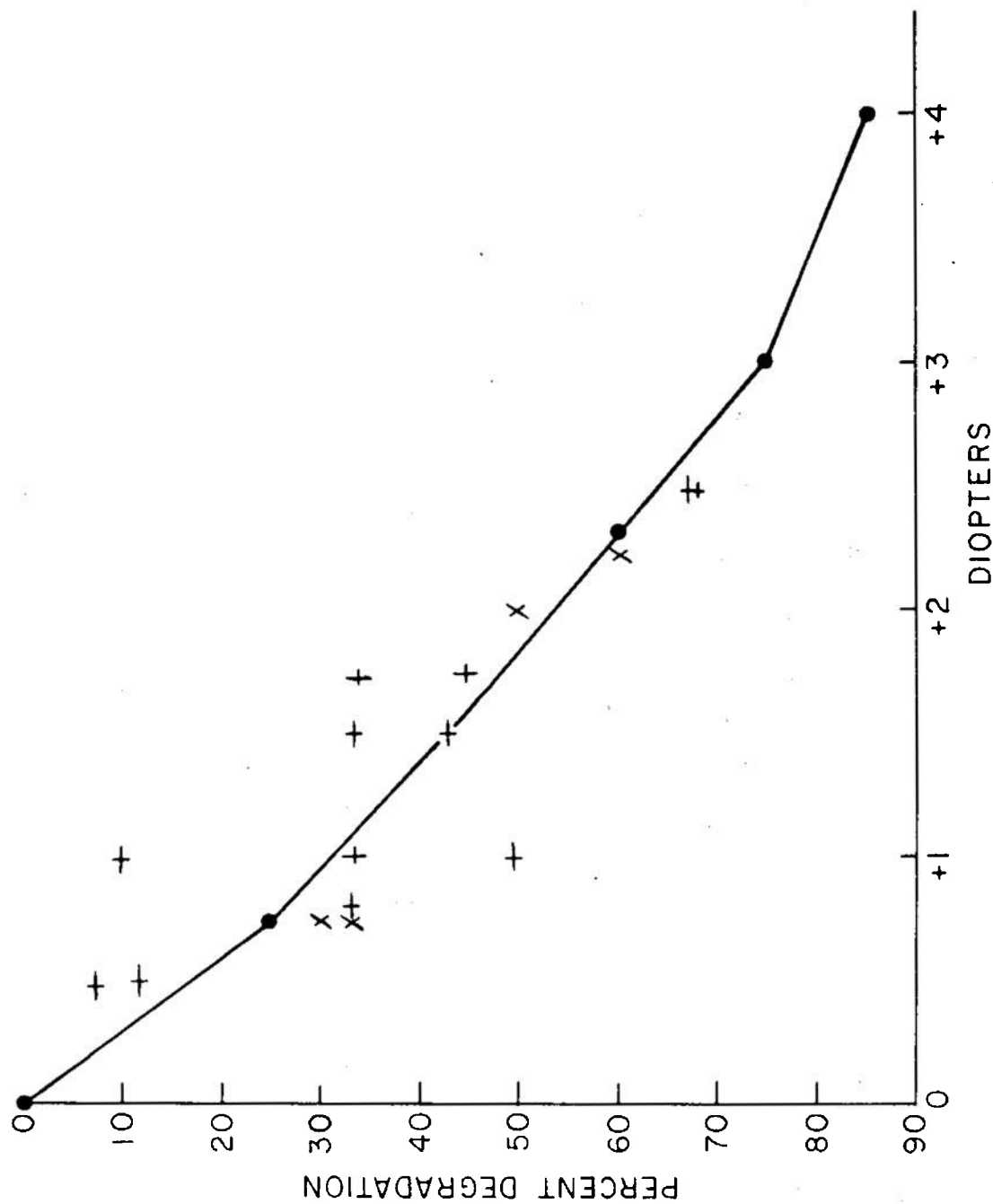


Fig. 4. The solid line shows the results of Fig. 3 replotted to show percent of degradation through cylinders of various powers compared to the results with no cylinder. The crosses show the same result for 15 natural astigmats. The orientation of the longer line in each cross shows the direction of distortion of the individual's astigmatism.

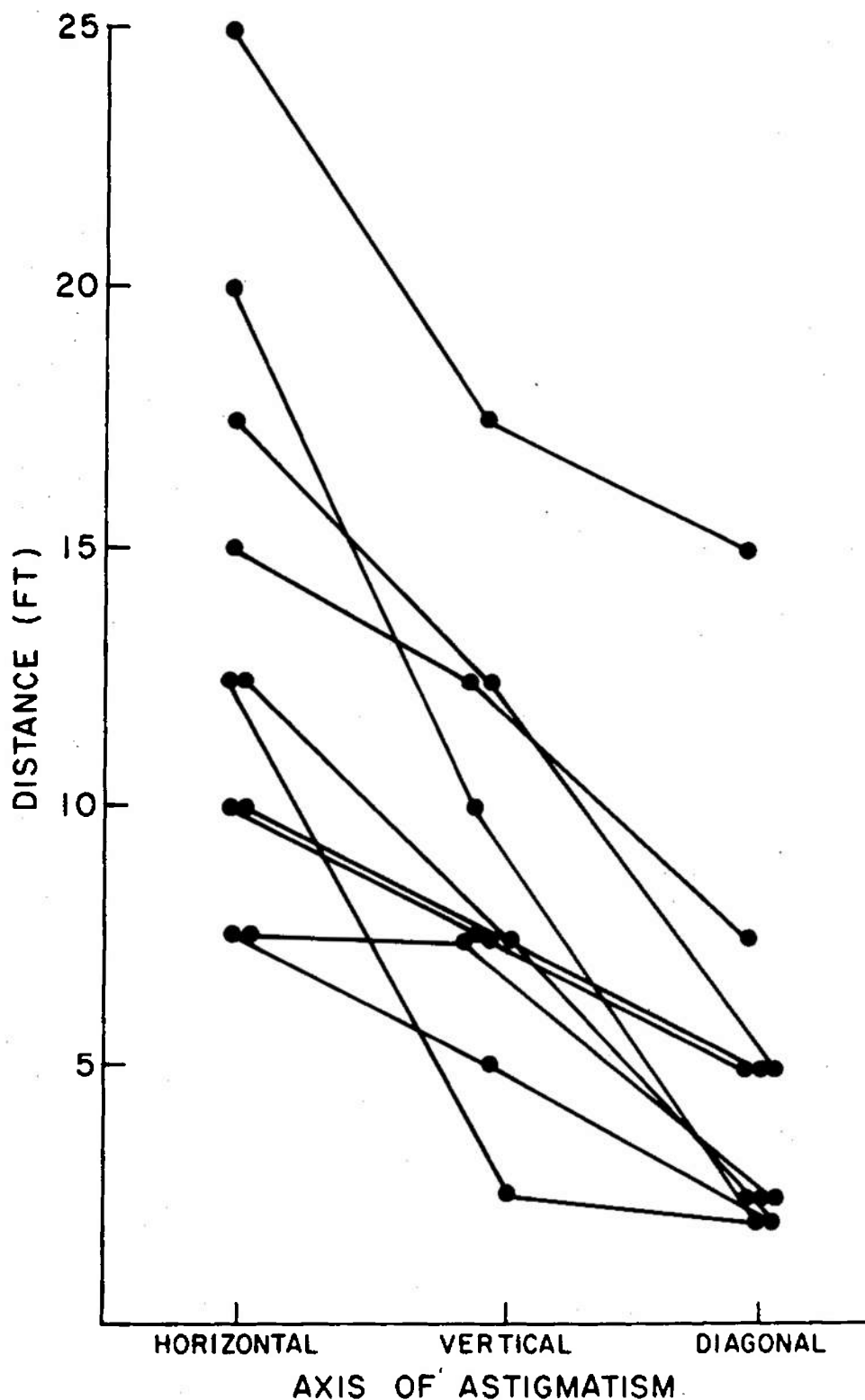


Fig. 5. Threshold distance for errorless ship identification for 10 observers viewing the targets through +2 diopter cylinder oriented either vertically, horizontally, or obliquely. A horizontal orientation produces minimal effect on details lying in the horizontal dimension; a vertical orientation produces minimal effect in the vertical dimension.

in the worst possible orientation, the mean threshold distance fell to less than 5 ft. At this very short distance, the overall length of the smallest ship subtended 198 min arc, or .15 cpd, which should not be affected by astigmatism: the ship should always be detectable, as indeed it was. But the largest mass of superstructure -on which correct identification presumably depended - was equal to .7 cpd, again within the region affected by astigmatism. These results conform satisfactorily with those for the gratings.

### Conclusions

Although the identification of ships is presumably a complex perceptual and cognitive skill, it is progressively degraded by increasing amount of astigmatism, and is the ability to perceive the high frequency gratings. It should be possible, therefore, to use sets of the more manageable gratings in place of ship silhouettes as test targets in a field study of actual periscopes.

Moreover, the second experiment also indicates that the results for natural and induced astigmats are reasonably consistent. That is, it is possible to adequately simulate astigmatism in emmetropes by the use of lenses. It is thus permissible to use induced astigmats, with the precise degree of astigmatism desired, as subjects in such experiments.

## EXPERIMENT III

### VISUAL PERFORMANCE THROUGH VARIOUS PERISCOPES

S. M. Luria, J. A. S. Kinney, C. L. Schlichting, A. P. Ryan

The first experiment demonstrated the utility of grating targets as a measure of the effects of astigmatism on visual performance, as well as providing data on the degradation of visual performance caused by current amounts of allowable astigmatism. Experiment I showed that astigmatism affects mainly the discrimination of high spatial frequencies. When the size of the target was large enough, astigmatic errors had a minimal effect on the observer's ability to see it. The first experiment also showed that the axis of astigmatism degraded acuity only when the axis was perpendicular to the stripes of the gratings.

The second experiment showed the effects of astigmatism on the perception of complex patterns and also demonstrated that induced astigmatism had the same effects as natural astigmatism. In the third experiment, we undertook to measure the effects of various amounts of

astigmatism on visual performance through different periscopes - more specifically, to determine if the performance of men with astigmatism (which did not exceed current visual standards) through an older periscope could be equalled by men with greater amounts of astigmatism through a newer periscope.

#### Method

Targets - In the field study of periscopes, one aim was to confirm the findings of the first two experiments that large targets, whether gratings or more complex forms such as ship silhouettes, were not affected by astigmatism. To test visual performance through the periscopes, it was deemed necessary to set up targets beyond optical infinity of the periscopes, which is generally taken to be 1200-1500 yards. However, at this distance, targets, in order to fall within the .4 cpd range that is not affected by astigmatism, would have to be very large. In order to simplify the threshold measurements, it was decided to vary the contrast of one large target rather than the spatial frequency. To measure contrast sensitivity, one has the choice of varying the contrast at a specific frequency or varying the frequency at a specific contrast. Thus, two sets of targets were constructed, a set of small targets of constant contrast that varied in spatial frequency, and a set of large targets of constant frequency that varied in contrast.

To measure high frequency thresholds, a series of high contrast targets consisting of black and white stripes was prepared. The contrast was .90 according to the formula

$$C = (L_L - L_D) / (L_L + L_D)$$

where  $L_L$  is the luminance of the lighter stripe and  $L_D$  is the luminance of the darker stripe.

The overall size of the targets was either 15, 27, or 48 inches square. On the smallest targets, the width of the stripes varied from .75 to 6 inches; on the intermediate targets, from 6 to 9 inches; on the largest targets, from 8 to 16 inches. Table I gives the visual angle subtended by the range of targets and the spatial frequencies in cycles per degree (cpd) of those targets.

To measure contrast thresholds for low frequency targets, a 4 x 8 ft background was painted a light gray whose reflectance was approximately .50. A set of 32 x 48 inch rectangles was prepared, painted in various shades of gray. When one of these rectangles was centered in front of the 48 x 96 inch background, it formed a target composed of three equal segments; the two outer segments were the background gray, and the center segment formed a contrast of either .00, .08, .12, .18, .23, or .66 .

Table I. Range of visual angle (deg) and spatial frequencies (cpd) of targets at the various magnifications

	Magnification					
	6X		12X		24X	
	V.A.	cpd	V.A.	cpd	V.A.	cpd
<u>High Contrast</u>						
Overall size (in)						
15"	.05		.10		.20	
48"	.16		.32		.65	
Stripe Width						
0.75	.003	195	.005	97	.01	48
6.0	.02	25	.04	12	.08	6
16.0	.05	10	.11	5	.22	2.5
<u>Low Contrast</u>						
Overall size						
96	.32		.65		1.31	
Stripe Width						
32	.11	4.5	.33	2.2	.44	1.1

Subjects - The subjects were military and civilian volunteers from the Medical Research Laboratory and the Periscope Research Laboratory. Four categories of observers were tested: 6 emmetropes, 6 astigmats who would meet the current Navy standards, and 5 more severe astigmats. Table II details the visual characteristics of the astigmatic observers.

Table II. Visual characteristics of the astigmatic observers

Visual Category	N	Mean Refractive error (diopters)	Range of error (diopters)
Mild astigmat	6	1.63	1.25 to 2.00
Severe astigmat	5	2.85	2.25 to 4.50

Experimental Plan - The visual performance of the various groups of observers was compared at three levels of magnification, 6, 12, and 24. In addition, some comparisons were made at 6 power between the new periscope and an older one. The performance of the astigmats was measured when they were both fully corrected and corrected only for any spherical error.

Since it is difficult to find enough observers with the range of astigmatic errors desirable for such an experiment, cylindrical errors were induced in emmetropes, and they were subjected to the most lengthy procedure. At the 12 and 24 power magnification, their performance was measured as their vision was progressively degraded up to 6 diopters of astigmatism; this was compared with their performance through the 6 power magnification when either undistorted or with 2 D of astigmatism. The purpose was to see how much astigmatism can be overcome by the magnification of the optical system to equal the performance through the lower power optical system of men who meet the current astigmatism standards. Astigmatism was always induced using positive lenses so that the subject would be unable to accommodate for it.

Procedure - The stripes of the targets were oriented either vertically or horizontally, depending on the axis of the observer's astigmatism, so as to be maximally blurred. (None of the astigmatic observers had oblique astigmatism.) For the observers with no natural astigmatism, the stripes were always vertical, and the induced astigmatism was always horizontal.

Thresholds were measured using the method of constant stimuli. The various conditions of cylindrical error were given in haphazard order. At each condition a range of target sizes was chosen which bracketed the observer's threshold. The various targets were presented several times, also in haphazard order, and the threshold was taken as the 50% point on the resulting frequency of seeing curve. Blank targets were also presented to curtail guessing.

The targets were displayed on a football field at a distance of 2800 yards from the periscope. The line of observation was to the southwest. Observations were made only in the morning, so that the sun was never behind the targets. Moreover, since the targets faced northeast, they were never in direct sunlight, greatly reducing the differences in illumination on the targets from sunny to cloudy days.



## Results

### Induced Astigmats

High Contrast Targets - Figure 6 shows the changes in high contrast stripe-width at threshold for emmetropic observers looking through various periscope settings as the cylindrical errors progressively increased. When observing through the older periscope at its maximum magnification, six power, the median threshold for normal observers was 3.25 inches. With two diopters of astigmatism, the maximum allowed for periscope operators, the median threshold rose to 6.5 inches. With the new periscope set at six power, thresholds under these conditions were noticeably worse. The reason is that an appreciable amount of light is diverted from the observer's eyepiece to the camera and television monitor. When the power of the new periscope is increased to 12X, we would expect the stripe-width threshold to be reduced to half, and it was, from slightly under 4 inches to 1.75 inches. When the observers were made 2 diopters astigmatic, the median threshold rose to 2.5 inches. Further increases in cylindrical refractive error produced a positively accelerating decline in acuity. When six diopters of astigmatism were introduced, the available targets could not be seen at all by the observers, and no threshold could be measured. Increasing the periscope power to 24X resulted in further decreases in target-size at threshold, and thresholds could be measured even with six diopters of astigmatism; the median threshold was 4.6 inches, appreciably better than the threshold with 2 diopters of astigmatism even with the older periscope.

Comparison of gratings and ship silhouettes - The ratio of the subject's performance under various amounts of astigmatism to that when fully corrected is compared in Figure 7 for the grating targets in this experiment and the recognition of the ship silhouettes in Expt. II. The ships were viewed with no magnification, of course, whereas the gratings were viewed through the periscopes at various levels of magnification. Figure 7 shows, as did Fig. 6, that as the magnification is increased, the deterioration of performance with increasing astigmatism increases less rapidly. In addition, the figure suggests that there is no discontinuity between viewing gratings and ship silhouettes.

Low Contrast Targets - Although the task in viewing the low contrast targets was to discriminate the presence of a lighter or darker stripe against the background, under certain, specific conditions, the subjects found it impossible to see the entire, large target at all. This is illustrated in Table III, which gives the number of individuals who failed to see the target under each condition. Without astigmatism, the target was clearly visible to all observers, but with the 6X magnification, even the smaller amounts of astigmatism had a deleterious effect. Although we did not measure thresholds

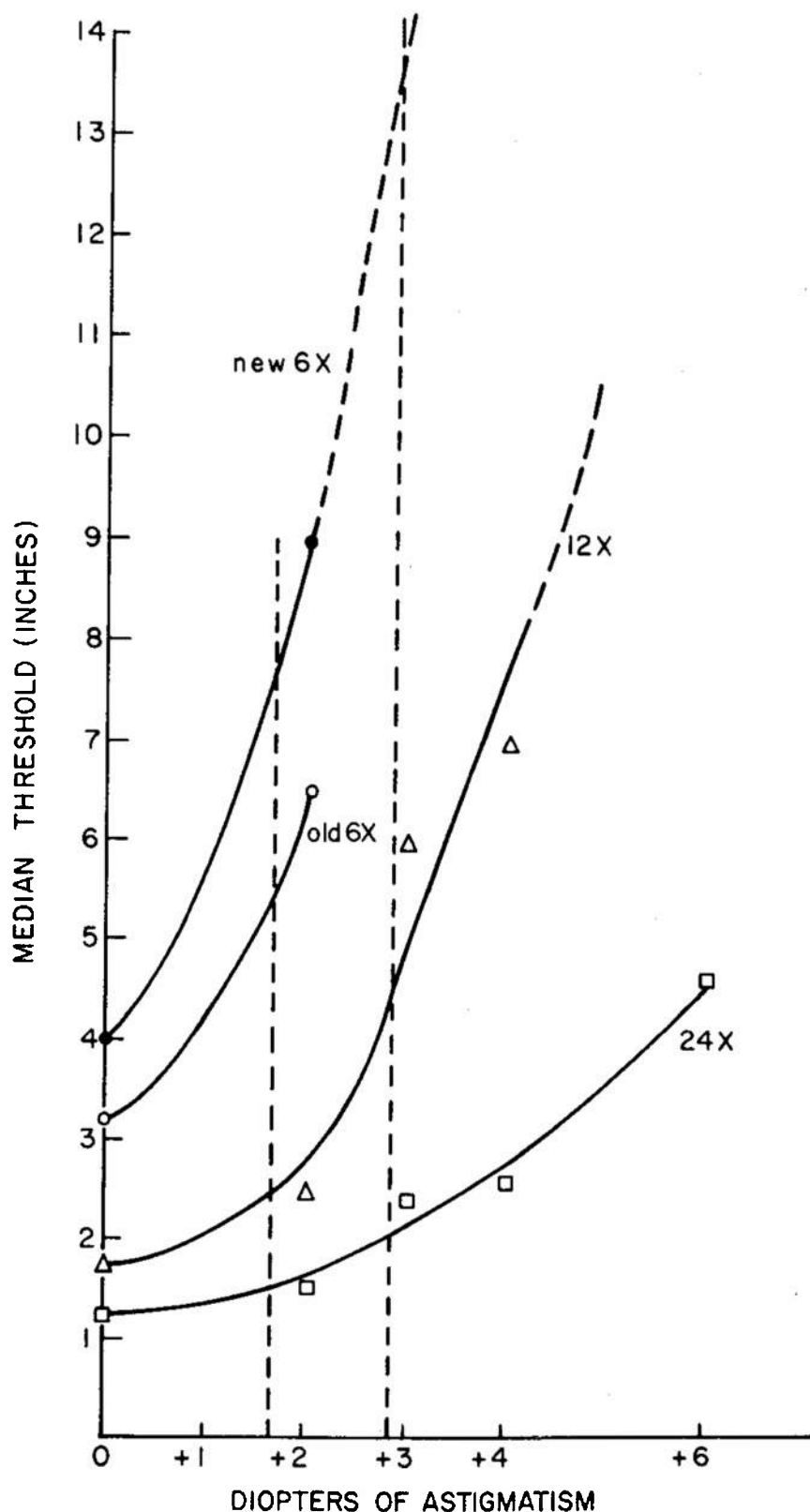


Fig. 6. Mean threshold width of high contrast, vertical target stripes through various periscope magnifications and the various magnitudes of cylindrical refractive error. The axis, or power, of the cylinder was horizontal. The vertical dashed lines indicate the mean astigmatic error for the two groups of natural astigmats.

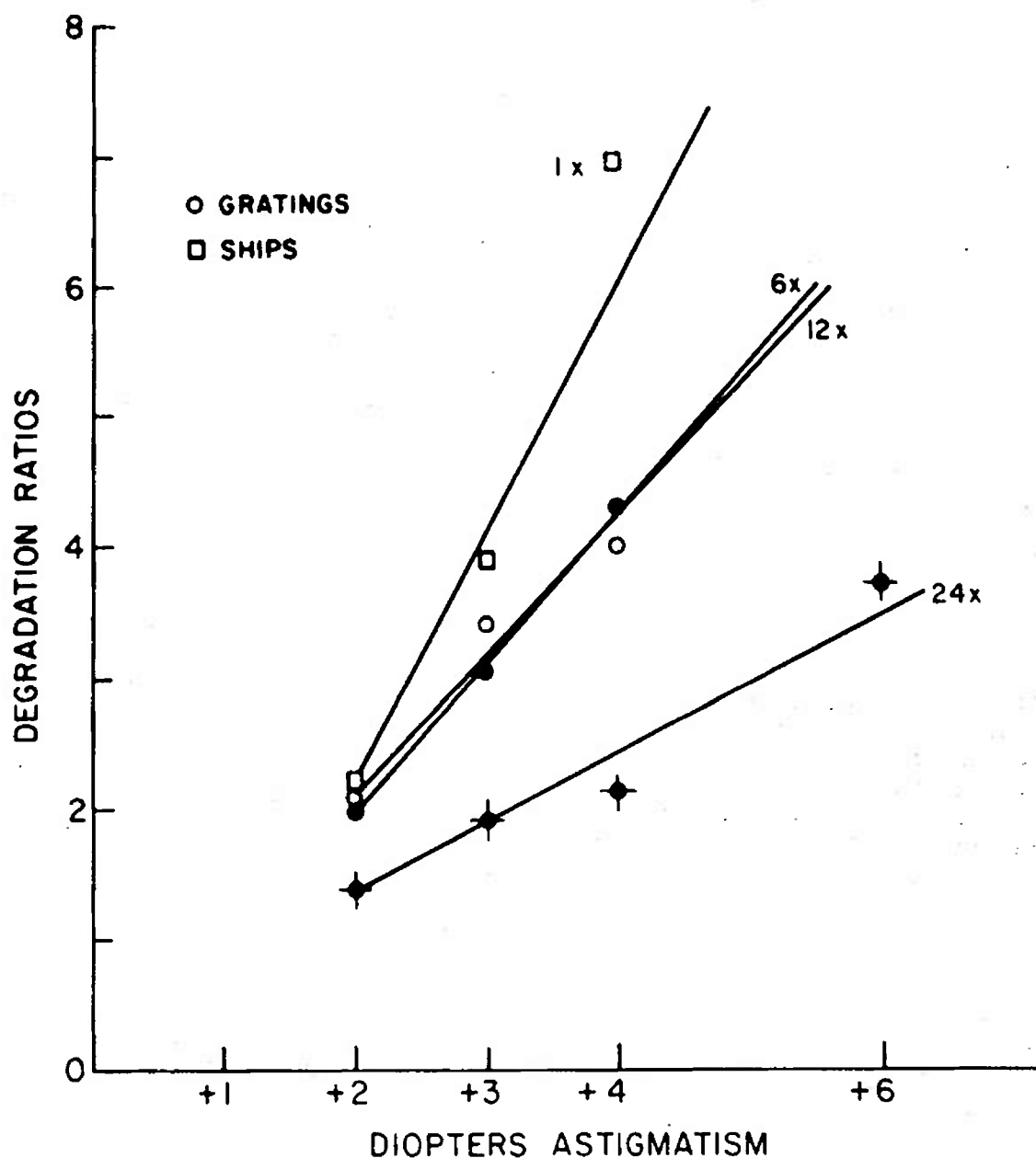


Fig. 7. Relative degradation of visual performance with increasing astigmatism for grating targets and for recognition of ship silhouettes. The gratings were viewed at various levels of magnification whereas the ships were viewed with no magnification.

Table III. Number of observers in each category who could not discern a low contrast target at the various magnifications and refractive errors.

Emmetropes (N=6)					
	0 D	2 D	3 D	4 D	6 D
6X	0	2	-	-	-
12X	0	1	1	3	5
24X	0	0	0	0	1

Mild Astigmats (N=6)			Severe Astigmats (N=5)	
	<u>Corrected</u>	<u>Uncorrected</u>	<u>Corrected</u>	<u>Uncorrected</u>
6X	1	3	0	3
12X	1	0	0	1
24X	0	0	0	1

of the emmetropes, casual reports by the subjects indicated that with still further increases in astigmatism under 6X, half of them could no longer make out the presence of a target with 3 D of astigmatism. On the other hand, when the magnification was increased to 12 power, most observers did not lose sight of the target until 4 D of astigmatism was induced, and with 24 power, all the observers except one could see the target under all conditions of astigmatism.

As long as the target could be seen, moreover, contrast thresholds for the stripe on the target changed very little as the amount of astigmatism was increased. These thresholds are given in Table IV. Although there were some variations in contrast threshold - e.g., from .04 to .10 at 24 power - these variations are modest when compared to the ranges available, and they all cluster at the most sensitive end. As long as the target is visible at all, the threshold remains reasonably constant, particularly in view of the fact that the highest contrast target was .66.

These data make sense in the context of the spatial frequencies presented in Expt. I. The low contrast target, 8 ft in length, can be viewed as a spatial frequency if we assume that the task is to differentiate it from the background. At 6 power, this becomes a

Table IV. Median contrast thresholds with various degrees of astigmatism and target magnification.

Diopters of Astigmatism	Old 6X	New 6X	12X	24X
0	.07	.065	.04	.04
2	.10	.18	.07	.04
3			.07	.10
4			*	.10
6			*	.105

\* Threshold could not be obtained.

1.5 cpd target; at 12 power, a .75 cpd target; and at 24 power, a .38 cpd target. Thus, its maximum size at 6 power is such that it could be adversely affected by 2 D of astigmatism (Fig. 1). The higher powers, however, enlarge the target enough to bring it into the range of the low spatial frequencies which are unaffected by astigmatism. At 24 power, or .38 cpd, the target remains visible and the contrast thresholds are roughly constant, even with 6 D of astigmatism.

#### Natural Astigmats

Table V compares the thresholds of the astigmatic observers when they were fully corrected and uncorrected under the various levels of magnification. The threshold data for corrected vision and for the conditions of mild astigmatism are in reasonable agreement with what would be expected on optical grounds: that is, when the magnification is doubled, the stripe-width at threshold is halved. For the severe astigmats, however, there was a disproportionate loss of acuity as magnification is reduced.

With the low contrast targets, there was again little variability in the thresholds as long as the targets could be discerned and thresholds could be measured. As Table IV shows, when they were corrected, virtually all the observers could see the target. Uncorrected, most could not see it at 6 power magnification. When the target could be seen and the median threshold could be calculated, it remained relatively constant.

Table V. Median thresholds for astigmatic observers either uncorrected or fully corrected.

	6X	12X	24X
Target-width thresholds (inches)			
<u>Mild Astigmats</u>			
Uncorrected	8.70	5.25	2.20
Fully corrected	6.50	2.50	1.60
<u>Severe Astigmats</u>			
Uncorrected	14.00	6.00	2.00
Fully corrected	6.50	3.00	1.50
Contrast Thresholds			
<u>Mild Astigmats</u>			
Uncorrected	*	.10	.10
Corrected	.10	.04	.10
<u>Severe Astigmats</u>			
Uncorrected	*	.10	.07
Corrected	.10	.09	.07

\* No threshold could be obtained.

#### Comparison of Natural and Induced Astigmatism

Table VI compares the results of the astigmatic observers with those of the emmetropic observers when the latter had induced the same mean level of cylindrical error as the natural astigmats. They agree reasonably well, although the values for the astigmats tend to be larger than those for the emmetropes with the same degree of cylinder error. The reason appears to be the atmospheric conditions

Table VI. Comparison of median thresholds for natural and induced astigmats with equivalent cylindrical error.

	High Contrast			Low Contrast*	
	6X	12X	24X	12X	24X
Mild Astigmats	8.7	5.25	2.20	0.10	0.10
Induced Astigmats	7.6	2.40	1.50	0.06	0.04
Severe Astigmats	14.0	6.00	2.00	0.10	0.07
Induced Astigmats	14.0**	4.40	2.20	0.07	0.08

\* Thresholds could not be obtained for natural astigmats and were not measured for induced astigmatic errors of more than 2 D at 6 power.

\*\* Estimated from Fig. 6.

under which the two groups observed. Observations were made under three conditions: sunny, overcast but clear, and slight haze. In reviewing the records, it turns out that only one of the six emmetropes observed on a hazy day, but half of the mild astigmats and two of the severe astigmats observed during hazy days. There seems to be little doubt that the discrepancy in the thresholds for the emmetropes and astigmats was caused by this uncontrolled field condition.

#### Discussion

Much of the present analysis is based on induced astigmatism in emmetropic observers. The first question which must, therefore, be answered is how similar is the visual performance of natural and induced astigmats. These results show that the thresholds for both the low and high contrast targets are very similar for the two sets of observers. In view of the small sample size, it is likely that any differences are simply the result of individual differences and the experimental errors of a field study. There is little reason to believe that the findings of this study would have been materially different had it been carried out on observers with various degrees of natural astigmatism.

As the degree of cylindrical error is increased, visual acuity is degraded in a positively accelerated curve. When the refractive error is greater than 2 diopters, the loss of visual acuity increases very sharply. But it is also clear that an increase in the magnification of

the target greatly offsets this degradation. This beneficial effect of an increase in magnification occurs for two reasons. First, the target size is increased, allowing smaller sized targets to be seen. This effect occurred for every subject. Second, the increase in target size may bring it into the range of low spatial frequencies that are not affected by astigmatism. This becomes a major benefit to astigmatic observers.

Since current Navy standards specify no more than 2 diopters of astigmatism, the practical question is how much refractive error can a periscope operator have and still see as well through the new periscope as a man with 2 diopters of astigmatism could see through the old periscope. Through the older periscope with its 6 power magnification, the median high contrast target threshold for emmetropes was about 3.25 inches under the present experimental conditions. With 2 diopters of astigmatism, the same observers required a target nearly twice as large. Yet using the 12 power magnification available on the new periscope, the same observers had better acuity with 3 diopters of astigmatism than they exhibited under 6 power magnification with only 2 diopters. Moreover, their acuity with 4 diopters of astigmatism was not appreciably better than is acceptable under current standards; indeed, it is almost as good as with the new 6 power periscope when there is no refractive error at all.

On the other hand, it is of interest that acuity through the new periscope is worse than the older periscope at the same magnification. This is undoubtedly because part of the available light is diverted to the camera and TV monitor. The additional degradation for a 2 diopter astigmat is almost as great as the degradation from no astigmatism to 2 D of astigmatism using the old periscope. If it were not for the increase in available magnification through the new periscope, it could be argued that it would be necessary to make the visual standards more stringent.

The results for the low contrast, high frequency thresholds showed that as long as the targets could be seen at all, there was little change in threshold. This occurred despite the fact that even at 24 power the largest target subtended only 1.2 degrees. Nevertheless, large threshold changes for a discernible target occurred only at the lowest magnification, when the total target area was, of course, only about 0.3 degree.

The lowest thresholds obtained in this study were .04, considerably worse than the best thresholds of .015 found in Expt. I. This was undoubtedly because of atmospheric haze, light losses through the periscope optics, and the like.



One final caution is that most of the data obtained in this study holds only for that case in which both the target and the axis of astigmatism have a specified orientation. We used the relative orientation of target and cylindrical error which would produce the worst performance. The Navy standards do not differentiate between various axes of astigmatism. However, a complex, natural target will have details with many orientations; consequently the perception of some details will always be degraded, no matter what the axis of orientation.

#### CONCLUSIONS AND RECOMMENDATIONS

These results indicate that there is no reason why the visual standards for both spherical and cylindrical errors cannot be relaxed. The greatly increased magnification available on the new periscope permits men with much greater refractive error to equal the performance on the old periscope of men who meet the current visual standards.

Compared to the old periscope, which had only 6 power magnification available, the performance of men with 2 diopters of astigmatism is very nearly equalled by men with 4 diopters of astigmatism using 12 power magnification; and with 24 power, even men with 6 diopters of astigmatism are appreciably better.

If the comparison is restricted to the new periscopes, then, of course, we are concerned with the difference in acuity resulting from an increase in maximum target magnification from 12 power to 24 power. Again, the performance of men with 2 diopters and 12 power is equalled by observers with 4 diopters and 24 power.

In summary, there seems to be no reason why astigmatism standards cannot be relaxed to permit periscope operators with at least 4 D of cylindrical error to be admitted to service.

The only consideration which might obviate this conclusion is the performance of periscope operators at night. Since the new periscope loses much of its light, there may be a disproportionate degradation of performance at night which does not occur in the daytime. Nighttime viewing may introduce noise into the system, which has been shown to place an upper limit on the useful magnification of a target and eventually to result in impaired performance with further magnification.<sup>2</sup> Nighttime performance was not measured in this study. Such an investigation would be worthwhile.

It would also be of great value to investigate the feasibility of providing full corrections for periscope operators with both spherical

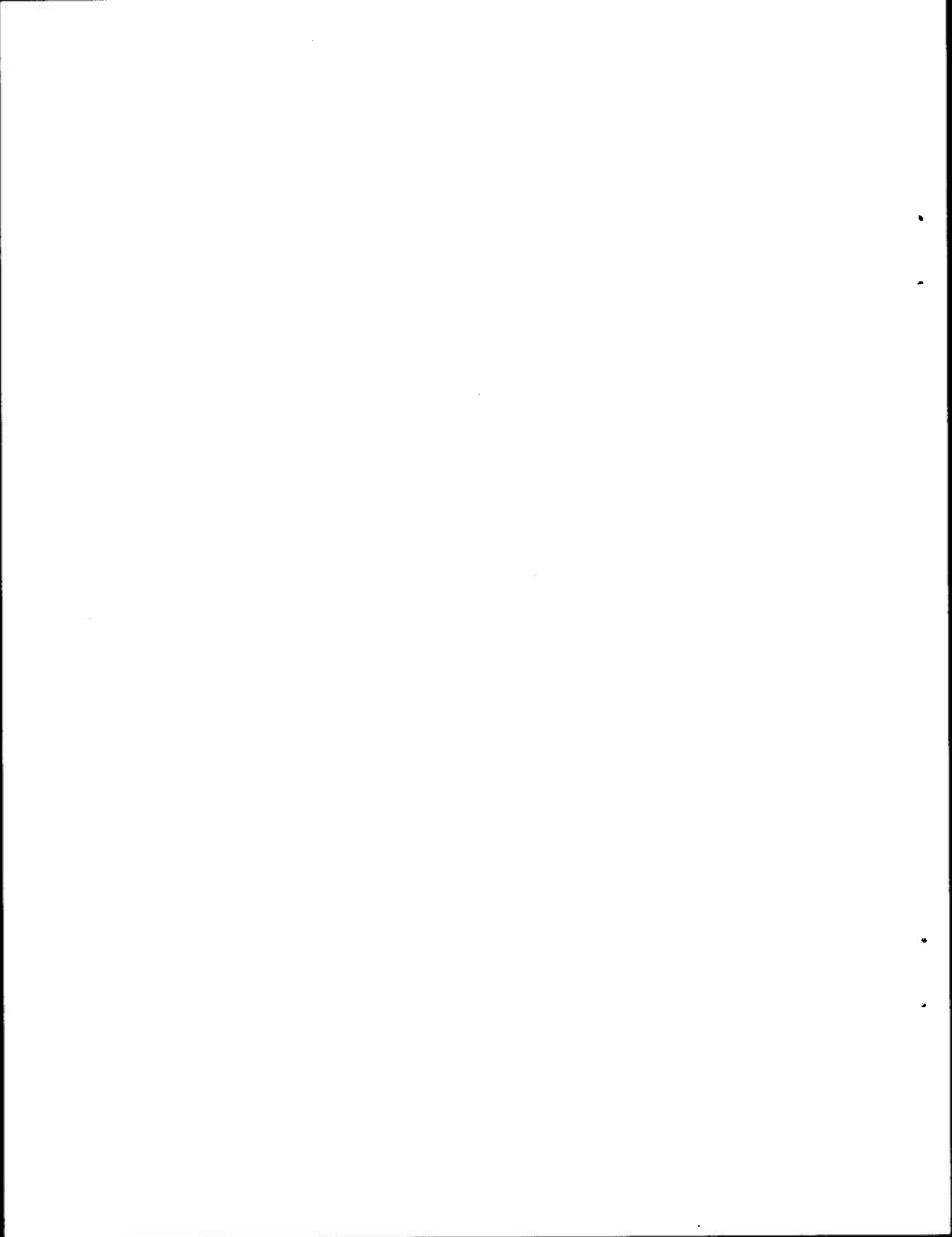
and cylindrical refractive errors. If this can easily be done without significant redesign of the instrument, it would eliminate the need for these visual standards.

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results are obtained with either gratings or ship silhouettes, and whether natural or induced astigmats are the observers.

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